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Solar cookers with and without thermal storage—A review

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ABSTRACT

The continuous increase in the level of green house gas emissions and the increase in fuel prices are the main driving forces behind efforts to more effectively utilize various sources of renewable energy. In many parts of the world, direct solar radiation is considered to be one of the most prospective sources of energy. Among the different energy end uses, energy for cooking is one of the basic and dominant end uses in developing countries. Energy requirement for cooking accounts for 36% of total primary energy consumption in India. Hence, there is a critical need for the development of alternative, appropriate, affordable mode of cooking for use in developing countries. However, the large scale utilization of this form of energy is possible only if the effective technology for its storage can be developed with acceptable capital and running costs. Thermal energy storage is essential whenever there is a mismatch between the supply and consumption of energy. Latent heat storage in a phase change material is very attractive because of its high storage density with small temperature swing. The choice of PCM plays an important role in addition to heat transfer mechanism in the PCM. In this present work a review has been made to study all the research and development work carried out in the field of solar cooker in particular the storage type solar cookers. A novel concept of PCM-based storage type solar cooker is also presented which is under experimental investigation.

Contents

1. Introduction

Cooking is the major necessity for people all over the world. It accounts for a major share of energy consumption in developing countries [1]. There is a critical need for the development of alternative, appropriate, affordable methods of cooking for use in

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developing countries [2]. Though there is a history for solar cooking since 1650, the interest in solar cooking was fuelled by the aftermath of the Second World War with its fuel shortages and rationing [3].

Solar energy has gained further importance in the current global discussions on energy and environment. As the world becomes more environmental conscious, there is a rising concern regarding deforestation and finding renewable energy options to fossil fuels. Currently, solar energy is meeting the vital energy requirements for a large percentage of the world's population particularly in developing countries. Among the different energy end uses, energy for cooking is one of the basic and dominant end uses in developing countries. Most of the thickly populated countries are blessed with abundant solar radiation with a mean daily solar radiation in the range of 5–7 kWh/m^2 and have more than 275 sunny days in a year [4]. Hence, solar cookers have a high potential of diffusion in these countries and offers a viable option in the domestic sector. It is identified as an appropriate technology as it has numerous advantages such as no recurring costs, potential to reduce drudgery, high nutritional value of food and high durability. Inspite of these advantages, the main hurdle in its dissemination are resistance to acceptance as it is a new technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues. The growing urban lifestyle also warrants faster cooking possible in future.

Hence a lot of research initiatives and promotional schemes are required for the successful commercialization of solar cookers as a substitute for conventional cooking devices. Promoting solar cookers help in conservation of conventional

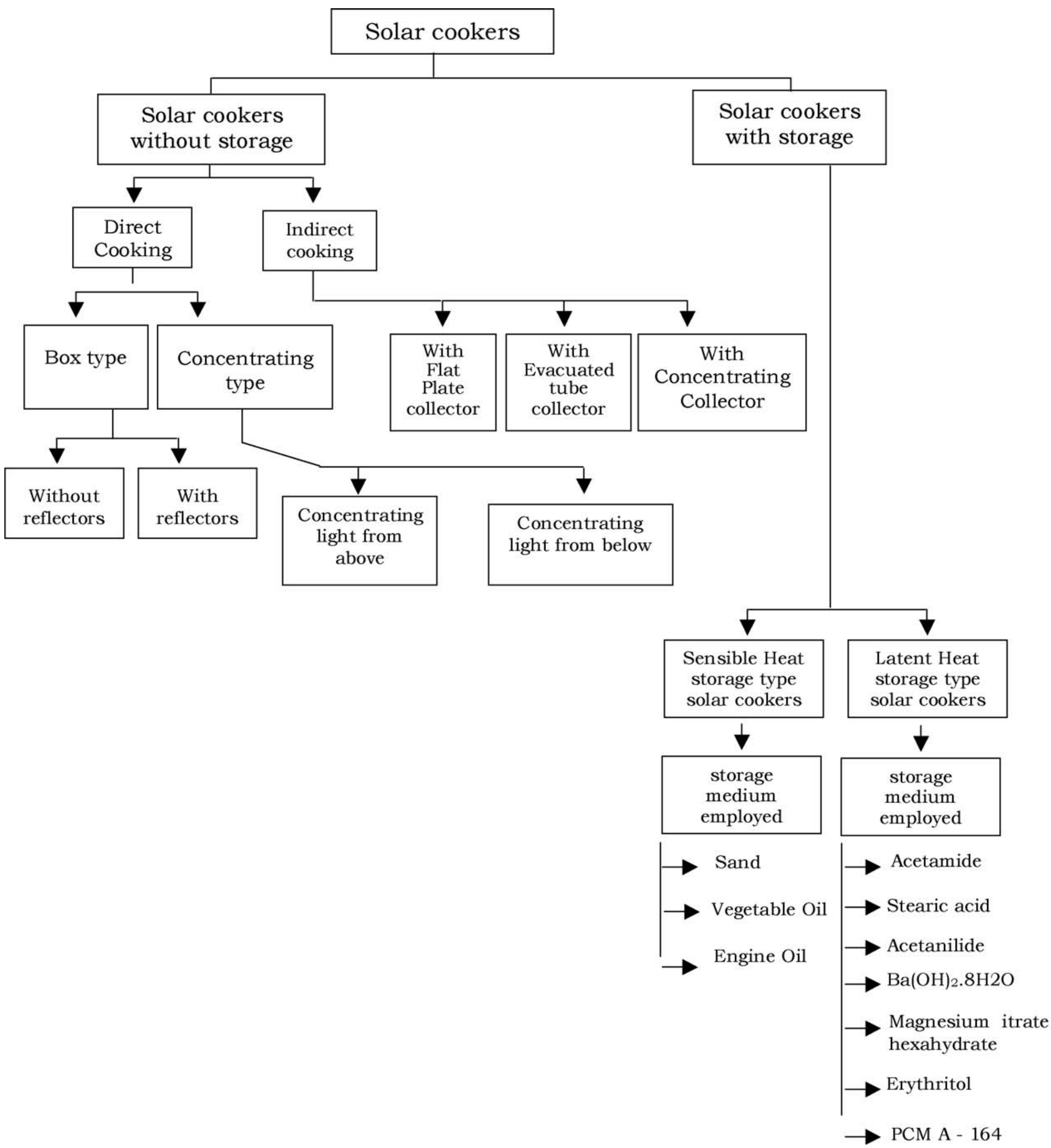

Fig. 1. Classification of solar cookers.

fuels such as firewood, animal dung and agricultural residues in rural areas and LPG, kerosene, electricity and coal in urban districts. Moreover the use of solar cookers would result in the reduction of the release of CO_2 in the environment. In this paper, a review has been carried out on the history of various types of existing/prevailing solar cooking options. The need for thermal storage in cooking and the various studies carried out with storage options are enumerated in detail. A novel concept of using phase change material (PCM A-164) for efficient and fast cooking is also presented.

2. Principle of cooking

Lof [5] has described the principles of cooking. As per his principle, the energy requirement is at maximum during the sensible heating period. Heat required for physical and chemical changes involved in cooking is less. The energy required for a specific cooking operation is not always well defined and can vary widely with the cooking methods used. During cooking, 20% of heat is spent in bringing food to boiling temperature, 35% of heat is spent in vaporization of water and 45% of heat is spent in convection losses from cooking utensils. Insulating the sides of the vessel and keeping the vessel covered with a lid can considerably reduce the heat losses.

So, once the contents of the vessel have been sensibly heated up to the cooking temperature, the speed of the cooking is practically independent of the heat rate, as long as thermal losses are supplied. Thus, differences in the time required to cook equal quantities of food are mainly due to different sensible heating periods.

3. Classification of cookers

In this present review, the available solar cookers are broadly categorised under two groups. (1) Solar cookers without storage and (2) solar cookers with storage. The classification of cookers under each group is shown in Fig. 1.

4. Solar cookers without storage

Solar cookers without storage are classified into direct and indirect solar cookers depending upon the heat transfer mechanism to the cooking pot. Direct type solar cookers use solar radiation directly in the cooking process while the indirect cookers use a heat transfer fluid to transfer the heat from the collector to the cooking unit.

4.1. Direct type cookers

Commercially successful direct type cookers are box type and concentrating type cookers.

4.1.1. Box type cookers

Box type solar cooker is an insulated container with a multiple or single glass cover. This kind of cooker depends on the green house effect in which the transparent glazing permits the passage of shorter wavelength solar radiation, but is opaque to most of the longer wavelength solar radiation coming from relatively low temperature heated objects. A double-walled insulated box can also serve to hold the heat inside the cooker. Mirrors may be used to reflect additional solar radiation into the cooking chamber. The speed of the cooking depends on the cooker design and thermal efficiency. The various types of box type cookers are shown in Fig. 2.

Ashok [6,2] summarizes the history of the development of the box type cookers. The very first design of box type cooker as shown in Fig. 2a was designed by Nicholas-de-Saussure. It was simply an insulated box with two glass panes forming the cover. This design forms the basis of all the present designs of box type cookers. Reflectors were added to increase the efficiency and the reliability of the simple box type cooker. Ghosh conceived box cooker with single reflector as shown in Fig. 2b. The design was a typical box type cooker with a double glazed cover and an additional reflector. Gosh type cooker works well during summer but additional boosters is essential during winter and this has resulted in the

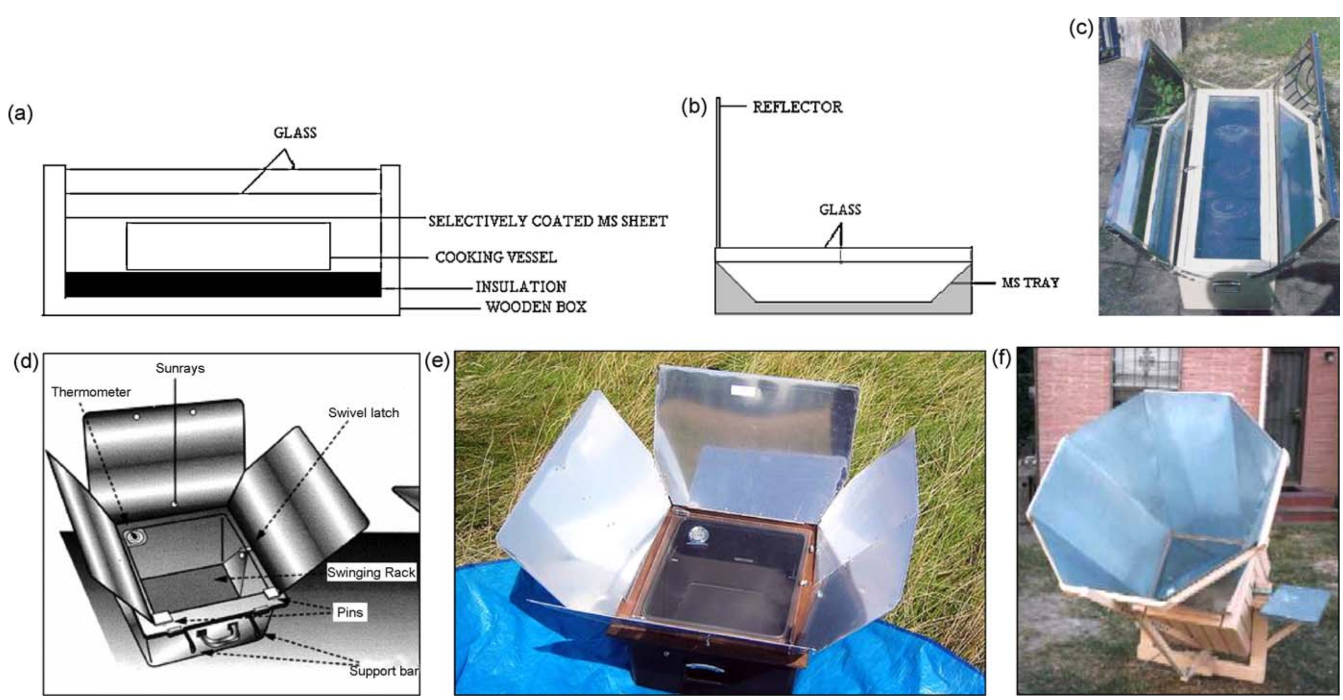

Fig. 2. Box type cooker: (a) without reflector, (b) with single reflectors, (c) with double reflectors, (d) with three reflectors, (e) with four reflectors and (f) with eight reflectors.

development of the box type cookers with double reflectors. Dutta has come out with an ingenious new concept for box type solar cooker with two reflectors as shown in Fig. 2c. To improve the performance further, three reflector design was proposed by Bowman (Fig. 2d). The reflectors have to be adjusted and tilted individually after setting. The box has to be turned to face the sun. The space between the mirrors has to be fitted with triangular mirrors to increase the efficiency further. These additional mirrors may come as add-on rather than as a part of the cooker. Halacy has gone a step further by suggesting a cooker with four reflectors as shown in Fig. 2e. He found that adjustment of the reflectors took a long-time and required several supports. The cooking time was not reduced by one-fourth as compared to single mirror cooker. However, it is essential that a designer should be aware of the existence of such a design in order to avoid further attempts in designing such a cooker. Maria Telkes was the first person to create a practical oven (box with four plus four reflectors) for daily work in 1959 and could develop a temperature of 225 °C. It was a rectangular double-walled insulated box with a door on each side. The box had double glazing fixed at the top and there were four main reflectors set at an angle of 60° to the horizontal. The corner spaces between these main reflectors were fitted with four triangular mirrors. The insulated box had a cradle frame to hold the cooking vessel and to assist in tilting.

Advantages of box cooker include simplicity of construction and operation with minimal attendance required during the cooking process. The cookers are also more stable. It can keep food warm for a long-time. Cookers do not produce glare and no risk of fire and burns. Disadvantages of solar box cookers include a slow cooking process due to low temperatures. Whenever there is an intermittent cloud, the food remains half cooked and hence gets wasted as it cannot be re-cooked even by using conventional fuels. The box type cookers even with booster mirrors has low concentration ratio up to 10 and low temperature up to 100 °C.

4.1.2. Concentrating type cookers

In the concentrating solar cookers [6], the cooking pot is placed at the focus of a concentrating mirror. Concentrating type solar cooker is working on one or two axis tracking with a concentration ratio up to 50 and temperature up to 300 °C, which is suitable for cooking. Concentrating cookers utilize multifaceted mirrors, Fresnel lenses or parabolic concentrators to attain higher temperatures. The various types of concentrating type cookers based on the mode of cooking are shown in Fig. 3.

Cookers that concentrate light from below and cookers that concentrate light from above are the two major types of concentrating solar cookers.

In the first type, the light is concentrated from above. Though this mode of concentration of energy from the top is not very desirable for cooking, there are several old designs, which have been developed. One of the most popular designs in this category is the solar panel cooker developed by Roger Bernard of France in 1994. Fig. 3a shows the schematic of panel cooker. It is elegant and simple looking, affordable, effective, and convenient solar cooker. It requires a dark covered pot and a high temperature plastic bag per month. Within few hours of sunshine, the cooker makes tasty meals for 4–5 persons at gentle temperatures, cooking food and preserving nutrients without burning and drying out. Fig. 3b shows the schematic of funnel cooker. It is simple to construct and store and there is hardly any wastage of sheet. The funnel support may pose problem in the beginning, however, it can be solved by making a small hole in the ground to hold the base of the funnel. Two small sticks or stones could be propped up at the back to hold the funnel in the right position.

In the second type, the light is concentrated from below and this mode is the most convenient for routine cooking. There are several designs developed in this type of cooker. Fig. 3c shows the schematic of spherical reflector. Stam first suggested this design in 1961. It is the simplest type of concentrator and is easy to build and use. The cooking vessel could be hung from the tripod or a suitable stand and positioned to meet the focus. Fig. 3d shows the schematic of parabolic reflector. They are popular among concentrating cookers because the focus is much better and sharper than that of other types of reflectors but at the same time it is very sensitive to even a slight change in the position of the sun and hence the use of such reflectors requires constant tracking. Though the parabolic reflector is a perfect design, even good technicians find it difficult to construct parabolic reflectors even with the help of templates. Hence the Fresnel reflectors as shown in Fig. 3e have gained importance. Three or four rings of Masonite (hardboard like material) are cut from $4' \times 4'$ sheet. Aluminum polyester is stuck to the rings after which the rings are nailed to specially notched wooden reapers to form a Fresnel concentrator. The cooking pot is supported on a rod projecting from the centre.

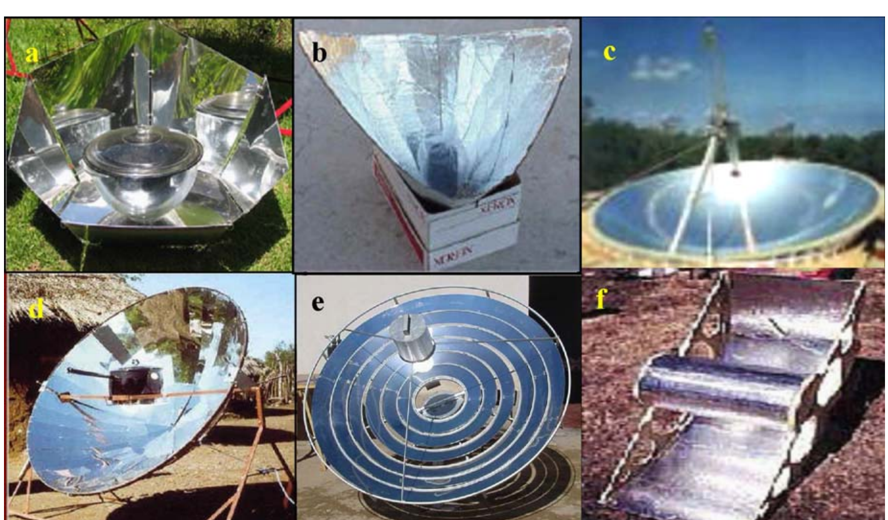

Fig. 3. Concentrating type cooker: (a) panel cooker, (b) funnel cooker, (c) spherical reflector, (d) parabolic reflector, (e) Fresnel concentrator and (f) cylindro-parabolic concentrator.

Fig. 3f shows the schematic of cylindro-parabolic concentrator. It focuses the rays into an insulated cylindrical box in which two or more cooking vessels can be accommodated. This design was common in water heating, however, later it was tried out for cooking as well, so as to cook food in more vessels.

Advantages of concentrating cookers include high cooking temperatures, cooking any types of food and short heat-up times. Disadvantages are their size, cost, the risk of fires and burns and the inconvenience to adjust the cooker as it requires frequent directional adjustment to track the sun.

4.2. Indirect type cookers

In indirect type solar cookers, the pot is physically displaced from the collector and a heat-transferring medium is required to convey the heat to the cooking pot. Solar cooker with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category. The various types of indirect type solar cookers are shown in Fig. 4.

Fig. 4a shows the schematic of flat-plate solar cooker developed by Schwarzer and Silva [7]. Schwarzer cookers can be incorporated into the construction of kitchen. Peanut or sunflower oil is used as heat transfer medium and the cooker is designed with two non-removing pots. Advantages of this cooker are possibility of fast cooking, large pot volumes and the possibility of indoor cooking and heat flow control in the pots. Solar cookers based on conventional flat-plate solar collectors suffer from the drawbacks such as the performance deteriorates due to the reversed cycle during night and cloudy periods of the day and high heat capacity. The further disadvantages are non-removable pots, which makes cleaning and dishing food difficult. Fig. 4b shows the schematic of vacuum tube collector-based solar cooker developed by Balzar et al. [8]. It consists of a vacuum tube collector with integrated long heat pipes directly leading to the oven plate. Solar cookers using vacuum tube collectors have several advantages. They do not need tracking. They can reach high temperatures and cooking can take place in the shade or inside a building because of the spatial separation of collecting part and oven unit. They require an effective heat transfer system in order to transfer the heat from the collector to the hot plate without a marked decrease of temperature. Heat pipes are very appropriate for this purpose. Their thermal conductance is extremely high and the heat transfer between the evaporator and the condenser section is nearly isothermal. Kumar et al. [9] designed the community type solar pressure cooker based on evacuated tube solar collector (ETSC). It consists of an evacuated tubular solar collector and a pressure cooker and both units are coupled together by heat exchanger. The incident solar irradiance falls onto the collector and heats up the working fluid inside the tubes. The vaporized fluid rises upwards to the heat exchanger and transfers energy by condensation to the water flowing in the secondary loop of the heat exchanger. The condensed fluid return back to the collector tubes and the process of heat transfer continues. It is observed that system based on ETSC supply heat at higher temperature (120 °C) than normal flat plate collector.

Fig. 4c and d shows the schematic of commercially successful solar steam cooking using parabolic concentrators at Tirumala Tirupathi Devasthanam in India and solar steam cooking using spherical reflectors at Auroville in Pondichery, India. The world's largest steam cooking system at Tirupathi Devasthanam comprises

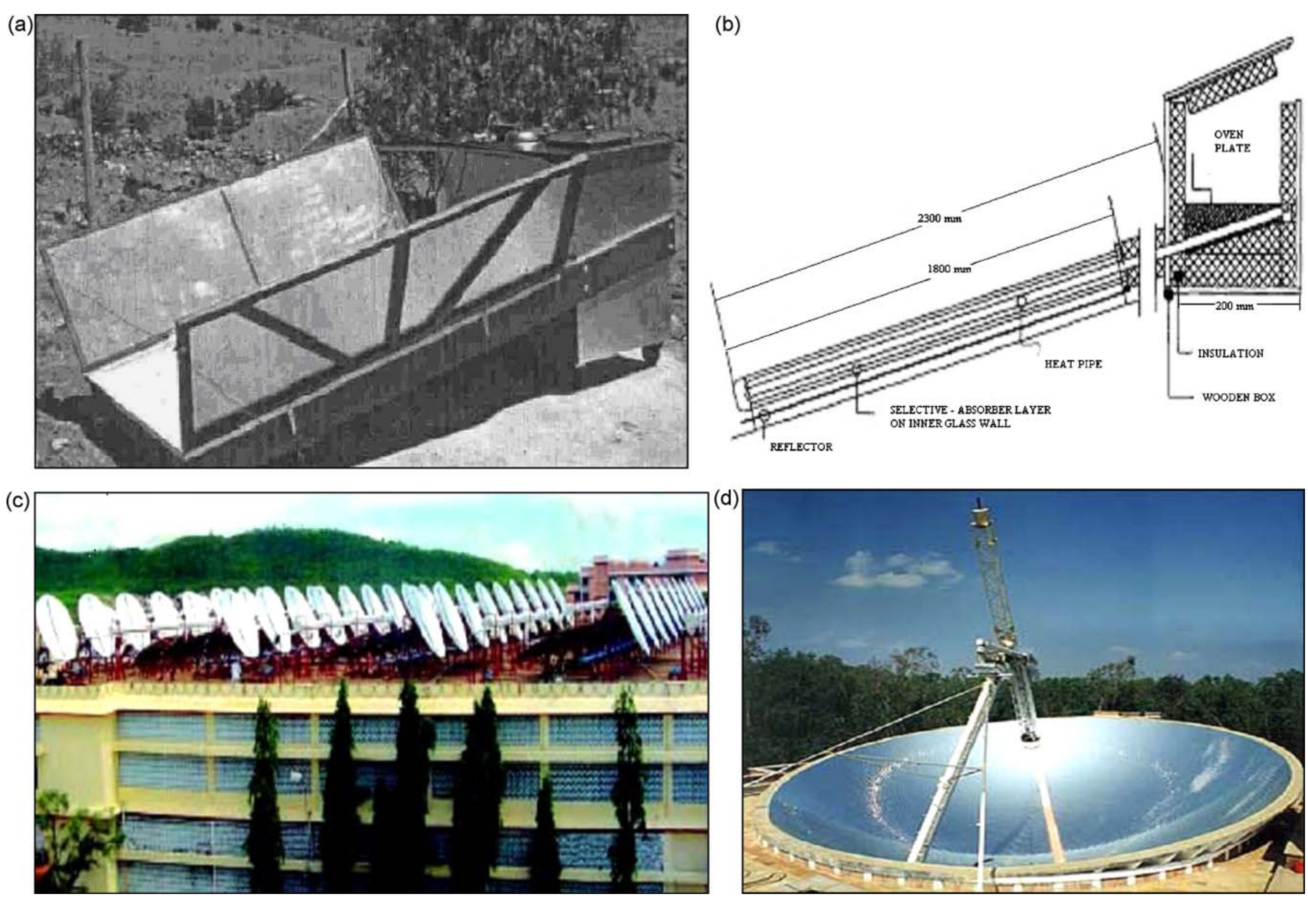

Fig. 4. Indirect type solar cooker: (a) with flat plate collector, (b) with evacuated tube collector, (c) parabolic concentrators at Tirumala Tirupathi Devasthanam and (d) spherical reflectors at Auroville.

106 roof top-mounted parabolic concentrators that generate steam for cooking up to 30,000 meals daily. The solar bowl at Auroville is 15 m in diameter and 7 m above the ground level. The ferrocement base of this stationery bowl faces south. The solar radiation trapped by a huge hemispherical mirror focuses on a cylindrical boiler which in turn follows the sun's position by means of a computerized tracking device. Steam at 150 °C can be generated in this boiler to cook meals for 1000 people.

Solar cookers are no longer presented as a total solution to cooking problems. They are being promoted as an add on cooking device with specific potential benefits and offering more choice and flexibility to consumers whom are normally forced to use specific fuels or appliance combinations because of affordability and accessibility issues. However, the large scale utilization of this form of energy is possible only if the effective technology for its storage can be developed with acceptable capital and running costs.

5. Solar cookers with storage

Thermal energy storage [10] is essential whenever there is a mismatch between the supply and consumption of energy. The solar cookers must contain a heat storage material to store thermal energy in order to solve the problem of cooking outdoors and impossibility of cooking food due to frequent clouds in the day or during off-sunshine hours. Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these. In this section, the different types of solar cookers which use sensible or latent heat storage materials are summarized.

5.1. Sensible heat storage

In sensible heat storage, thermal energy is stored by raising the temperature of a solid or liquid. Fig. 5 shows the various types of sensible heat storage type solar cookers.

Fig. 5a shows the schematic of a hot box cooker with used engine oil as a storage material developed by Nahar [4]. The device consists of a double-walled hot box. The outer box is made of 22 SWG galvanized steel sheet. The inner box is also a double-walled tray and made of 22 SWG aluminum sheet. The dimensions of the outer box are 610 mm × 610 mm × 200 mm and the inner box are 450 mm × 450 mm at the top and 415 mm × 415 mm at the bottom with 80 mm height. The space between the inner trays is filled with 5.0 kg of used engine oil and it is completely sealed. The space between the outer tray and the outer box is filled with glass wool insulation and separated by a wooden frame. The inner tray is painted black with black board paint. Two clear window glass panes of 4 mm thickness have been fixed over the inner tray with an openable wooden frame. A rubber gasket is provided between the tray and the openable frame to make it leak proof. A 4 mm thick plane mirror reflector is fixed over it. The reflector can be placed

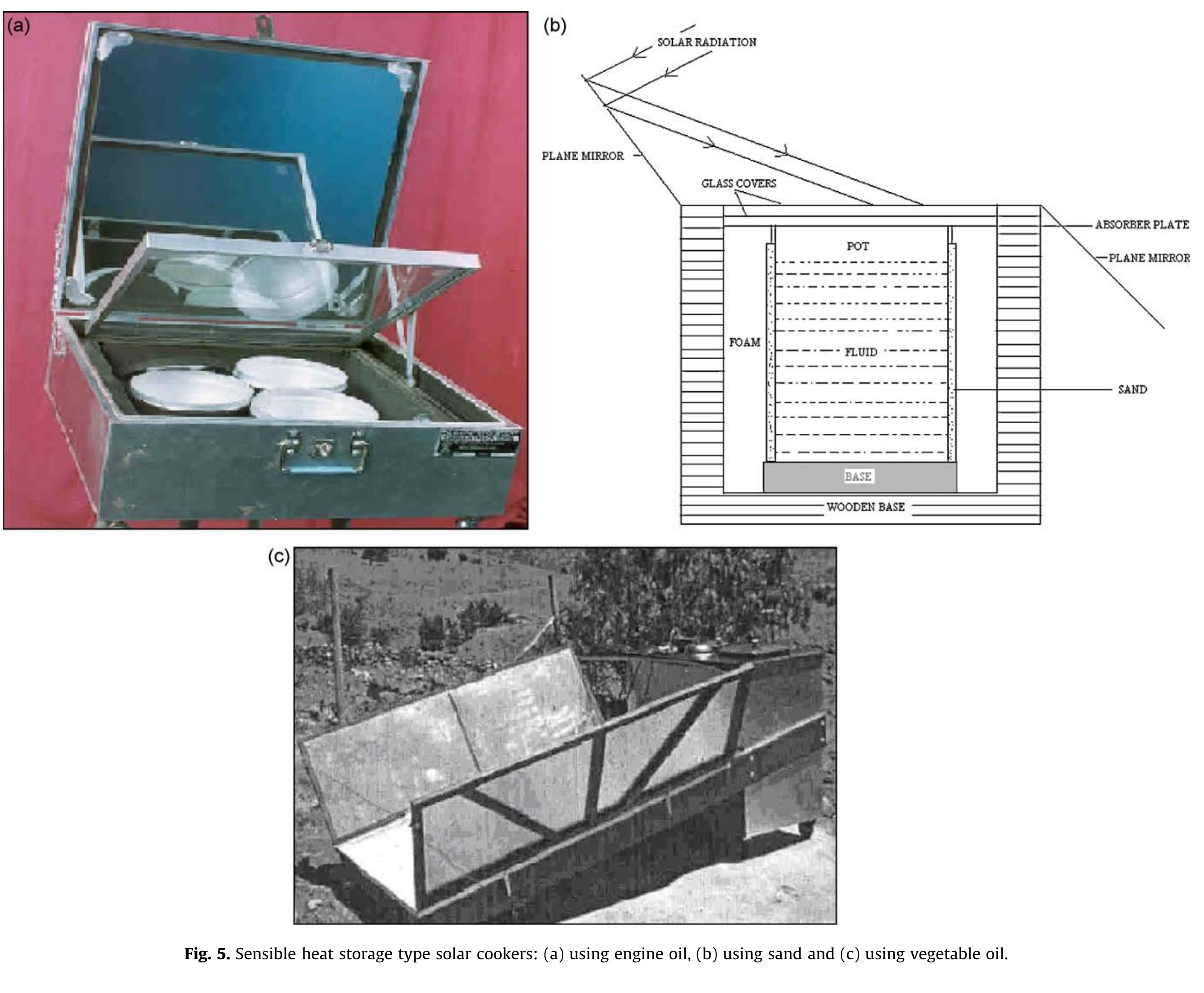

Fig. 5. Sensible heat storage type solar cookers: (a) using engine oil, (b) using sand and (c) using vegetable oil.

over the cooker and acts as a lid. The tilt of the reflector can be varied from 0° (closed lid) to 120° from the horizontal plane depending upon the season. The overall dimensions of the cooker are 610 mm × 610 mm × 275 mm. Four cooking utensils of 200 mm diameter can be kept inside the cooker for cooking four dishes simultaneously. The maximum stagnation temperature attainable inside the cooking chambers of the hot box solar cooker with storage material is the same as that of the hot box solar cooker without storage during the daytime, but it is 23 °C more in the storage solar cooker from 17.00 to 24.00 h.

Fig. 5b shows the schematic of flat-plate solar cooker using sand as storage medium developed by Ramadan et al. [11]. It consists mainly of a wooden box with one opening. The inner box dimensions are 0.25 m × 0.25 m × 0.30 m. A copper absorbing flat plate (0.25 m × 0.25 m) painted matt black with two glass covers (3 mm thick) and 25 mm apart is placed on top of the box. The cooking pot is a copper cylinder of size 0.002114 m^3. The pot cover is welded to the absorbing plate to obtain maximum possible thermal conduction. The whole pot is resting on a wooden base. Four reflecting plane mirrors of (0.30 m × 0.30 m) each are attached to the sides of box to concentrate the solar insolation according to the angle of incidence. These mirrors can be handled simply by tilting each mirror at a certain time without changing the cooker's position. NiCr–Ni thermocouples for temperature measurements are suitably located at different parts of the cooker. The cheapest storage material and the best performance were achieved by making a jacket of sensible heat storage material such as sand of 0.5 cm thick. Six hours/day of cooking time has been recorded and approximately 3 h/day of indoor cooking has been achieved.

Fig. 5c shows the schematic of flat-plate solar cooker developed by Schwarzer and Silva [7] using vegetable oil as storage medium. The system consists of one or more flat plate collectors with a coated absorber and double glazed covering, cooking pots and a storage tank to store thermal energy. Vegetable oil is used as the heat transfer fluid. The oil is heated up in the collectors and moves by natural flow to the cooking unit, where it transfers part of its sensible energy to the double-walled cooking pots. Manually controlled valves guide the oil flow rate either to the pots or to the storage tank. The major advantages are the possibility of indoor cooking, the use of a thermal storage tank to keep the food warm for longer periods of time or night cooking and the reach of high temperatures of the working fluid in a short period of time.

The major limitations of sensible heat storage materials include low specific heat capacity and the decrease in effectiveness of cooking as the temperature of the storage material decreases during discharging.

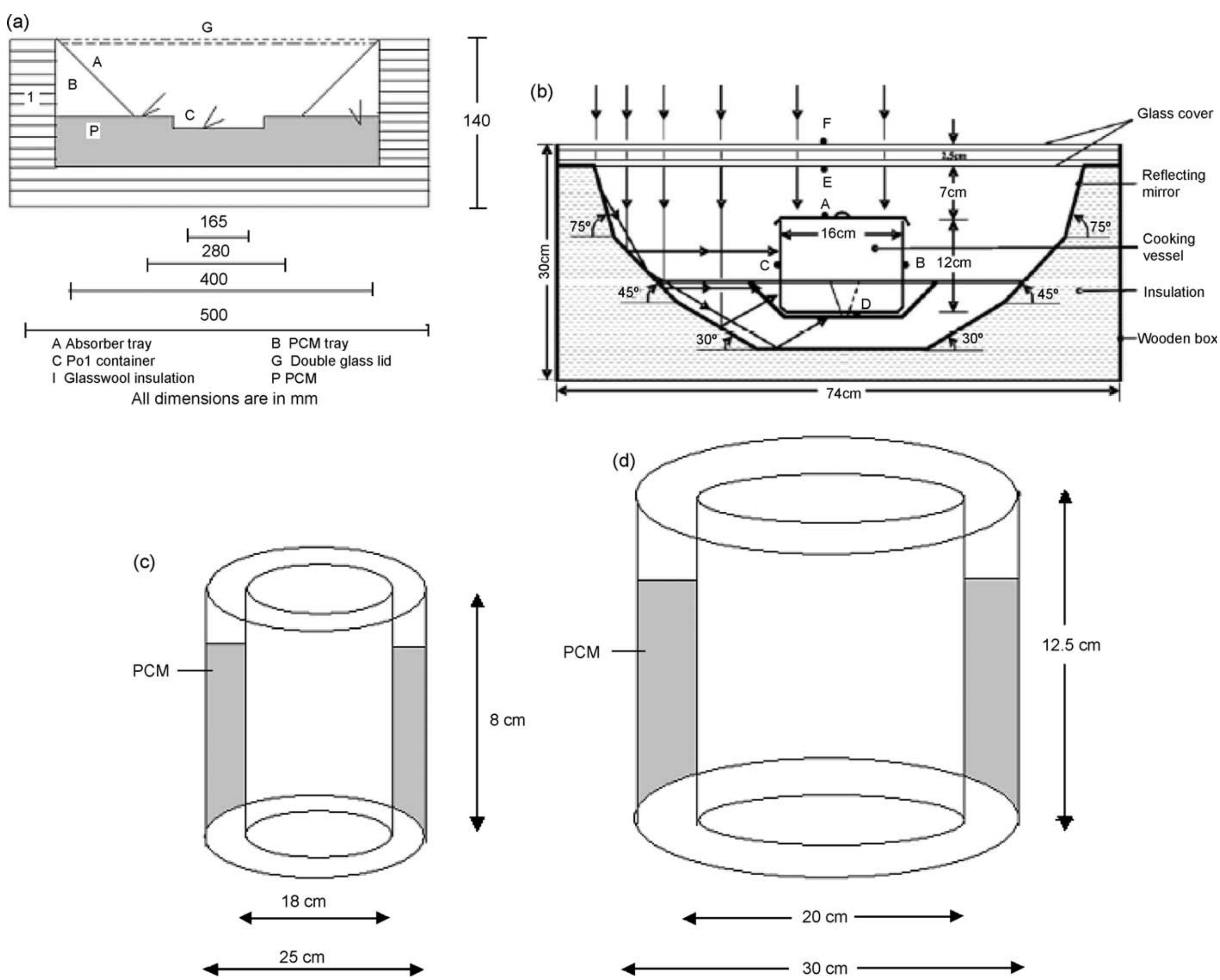

Fig. 6. Box type solar cookers with latent heat storage: (a) Buddhi et al. model, (b) Domanski et al. model, (c) Sharma et al. model and (d) Buddhi and Sharma model.

5.2. Latent heat storage

Latent heat storage [12,13] makes use of the energy stored when a substance changes from one phase to another. The use of PCMs for storing heat in the form of latent heat has been recognized as one of the areas to provide a compact and efficient storage system due to their high storage density and constant operating temperature. In this section, different types of solar cookers integrated with PCM as thermal storage medium developed by different researchers are studied and given in detail. Fig. 6 shows the various box types cookers integrated with phase change materials.

Buddhi and Sahoo [14] designed and tested a solar cooker as shown in Fig. 6a with latent heat storage for cooking food in the late evening. In this design, the phase change material (PCM) was filled below the absorbing plate. Commercial grade stearic acid (melting point 55 °C, latent heat of fusion 161 kJ/kg) is used as a latent heat storage material. In such type of design, the rate of heat transfer from the PCM to the cooking pot during the discharging mode of the PCM is slow and more time is required for cooking food in the evening.

Fig. 6b shows the schematic of solar cooker with PCM cooking container developed by Domanski et al. [15]. He investigated the possibility of cooking during non-sunshine hours using phase change materials (PCMs) as storage media. For this purpose, two concentric cylindrical vessels (0.0015 m thick), made from aluminum are connected together at their tops using four screws to form a double-walled vessel with a gap between the outer and inner walls. The outer and inner vessels have a diameter of 0.18 and 0.14 m. The annular gap between the outer and inner vessels is 0.02 m. This gap is covered with a removable aluminum cover into which three circular holes were drilled to allow inserting of thermocouples and permit direct visualization during filling or removing of the PCMs. A circular aluminum cover is used as the lid for the inner vessel. The gap between the outer and the inner vessels is filled with 1.1 kg of stearic acid (melting temperature 69 °C) or 2 kg of magnesium nitrate hexahydrate (melting temperature 89 °C) which leaves sufficient space for expansion of the PCMs on melting. The cooker performance was evaluated in terms of charging and discharging times of the PCMs under different conditions. They reported that the performance depends on the solar irradiance, mass of the cooking medium and the thermo physical properties of PCM. The overall efficiency of the cooker during discharging of the PCM was found to be 3–4 times greater than that for steam and heat-pipe solar cookers, which can be used for indoor cooking. However, the rate of heat transfer from the PCM to the cooking pot is slow, and more time is required for cooking evening meal.

Sharma et al. [16] designed and developed a cylindrical PCM storage unit for a box type solar cooker to cook the food in the late evening. Since the PCM surrounds the cooking vessel, the rate of heat transfer between the PCM and the food is higher and cooking can be faster. For this purpose, a PCM container was designed and fabricated as shown in Fig. 6c to hold the cooking vessel. It has two hollow concentric aluminum cylinders of diameter 18 and 25 cm and is 8 cm deep with 2 mm thickness. The space between the cylinders is filled with acetamide (melting point 82 °C, latent heat of fusion 263 kJ/kg) as a PCM. The dimensions of the vessel used for cooking are 17.5 and 10 cm in diameter and height, respectively, and it can be inserted inside the PCM container for cooking purpose. To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container, eight fins (1 cm × 3 cm) are welded at the inner wall of the PCM container. They reported that by using 2 kg of acetamide as a latent heat storage material, the second batch of food could be cooked if it is loaded before 3.30 p.m. during the winter season. They recommended that the melting temperature of a PCM should be between 105 and 110 °C for evening cooking. Therefore there was a need to identify a storage material with appropriate melting point and quantity, which can cook the food in the late evening. More input solar radiation is required to store a larger quantity of heat in a PCM.

Buddhi and Sharma [17] later developed a latent heat storage unit as shown in Fig. 6d for a box type solar cooker with three reflectors. They use acetanilide (melting point 118 °C, latent heat of fusion 222 kJ/kg) as a PCM for night cooking. To conduct the cooking experiment with the PCM storage unit, a double glazed (glass covers) box type solar cooker having 50 cm × 50 cm aperture area and 19 cm deep is used. In this solar cooker, three reflectors are provided; (i.e.) the middle reflector is mounted with a hinge and had rotation only about the horizontal axis. The other two reflectors are fixed by a ball and socket mechanism in the left and right sides of the reflector. This pair of reflectors has three degrees of freedom, (i.e) they can have movement about the horizontal axis and vertical axis and can rotate about both the axes. By these mechanisms, efforts were made to keep the reflected solar irradiance on the absorber surface to enhance the incident solar radiation on the glass cover during the course of the sun exposure experiments. A cooking vessel with latent heat storage was designed and fabricated to facilitate cooking food at night. This unit is similar to the cooking unit designed by Sharma et al. [16] except the dimensions and the quantity of PCM used.

Further development has been made with PCM-based storage type cooker to facilitate indoor cooking. Ramadan et al. [11] has given a theoretical concept of using PCM material for indoor cooking in 1987. They designed a simple flat-plate solar cooker as shown in Fig. 7 with focusing plane mirrors using energy storage materials.

The possibility of using PCM as a storage medium to obtain longer cooking periods was studied. A thin layer of the salt hydrate $Ba(OH)_2 \cdot 8H_2O$ as a jacket around the cooking pot was suggested. Bushnell [18] presented a prototype for solar ovens, which employs a pentaerythritol as a solid–solid PCM. He described the performance from efficiency measurement and determination of figure of merit [19].

Sharma et al. [20] developed a solar cooker based on evacuated tube solar collector (ETSC) with PCM storage as shown in Fig. 8.

It consists of an ETSC, a closed loop pumping line-containing water as heat transfer fluid (HTF), a PCM storage unit, cooking unit, pump, relief valve, flow meter and a stainless steel tubular

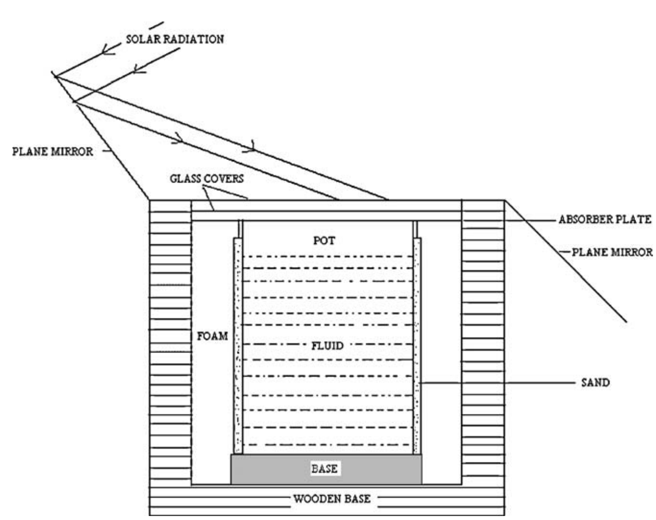

Fig. 7. Latent heat storage type flate plate solar cooker using $Ba(OH)_2 \cdot 8H_2O$ as PCM.

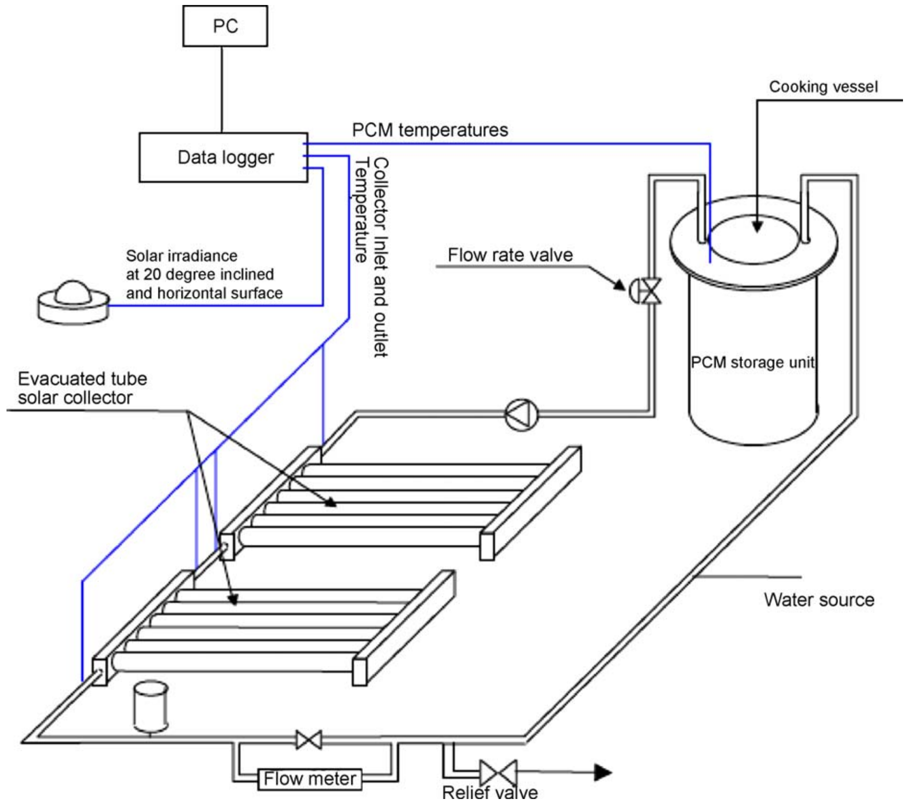

Fig. 8. Latent heat storage type evacuated tube solar cooker using erythritol as PCM.

heat exchanger. The PCM storage unit has two hollow concentric aluminum cylinders, and their inner and outer diameters are 304 and 441 mm, respectively, and are 420 mm deep with 9 mm thick. The space between the cylinders is filled with 45 kg erythritol (melting point 118 °C, latent heat of fusion 339.8 kJ/kg) used as the PCM. A pump circulates the heated water (HTF) from the ETSC through the insulated pipes to the PCM storage unit by using stainless steel tubular heat exchanger that wraps around the cooking unit by closed loop. During sunshine hours, heated water transfer its heat to the PCM and stored in the form of latent heat, through a stainless steel tubular heat exchanger. This stored heat is utilized to cook the food in the evening time or when sun intensity is not sufficient to cook the food. They concluded that two times cooking (noon and evening) is possible in a day. Noon cooking did not affect the cooking in the evening and evening cooking using PCM storage was found faster than noon cooking. Experiments and analysis indicated that the prototype solar cooker yielded satisfactory performance inspite of low heat transfer. The modified design of heat exchanger in the thermal storage unit will enhance the rate of heat transfer in the present set-up.

Hussein et al. [21] developed a novel indirect solar cooker as shown in Fig. 9 with outdoor elliptical cross-section wickless heat pipes, flat-plate solar collector with an integrated indoor PCM thermal storage and cooking unit.

Two plane reflectors are used to enhance the insolation falling on the collector, while magnesium nitrate hexahydrate (melting temperature 89 °C, latent heat of fusion 134 kJ/kg) is used as the PCM inside the indoor cooking unit of the cooker. It is found that the average daily enhancement in the solar radiation incident on the collector surface by the south and north facing reflectors is about 24%. Different experiments have been performed on the solar cooker without load and with different loads at different loading times to study the possibility of benefit from the virtues of the elliptical cross-section wickless heat pipes and PCMs in indirect solar cookers to cook food at noon and evening and to keep food warm at night and in early morning. The results indicate that the present solar cooker can be used successfully for cooking different kinds of meals at noon, afternoon and evening times, while it can be used for heating or keeping meals hot at night and early morning.

6. Investigation using PCM A-164 as storage material

The maximum temperature of the phase change material in storing heat for solar cooking reported in the literature is only

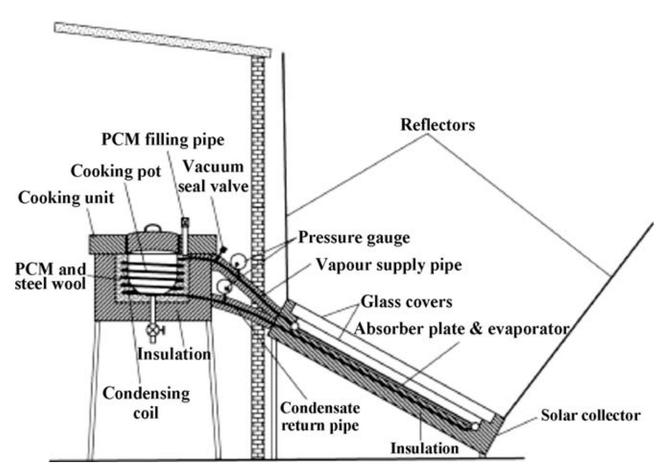

Fig. 9. Latent heat storage type flate plate solar cooker using magnesium nitrate hexahydrate as PCM.

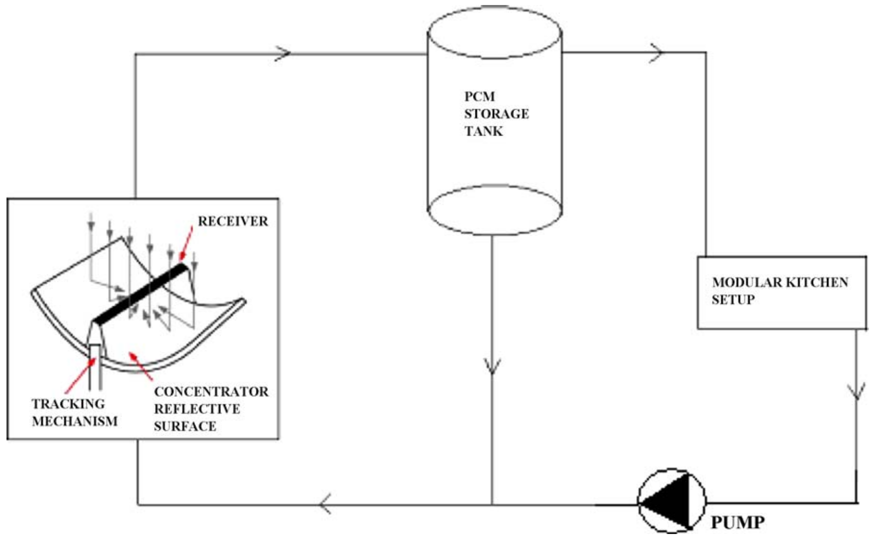

Fig. 10. Latent heat storage type concentrating solar cooker using PCM A-164.

around 120 °C. Moreover when PCM is used as a storage material in solar cooking, the indirect mode of heating is most suitable which again makes a temperature drop of approximately 10–15 °C between the cooking vessel surface and the storage material. Hence a maximum cooking vessel surface temperature of 100 °C is only possible which is not suitable for frying and fast cooking.

In the present work, solar cooking system using PCM A-164 [22] as the storage medium is under investigation and the concept diagram is shown in Fig. 10.

This system consist of a concentrating type solar collector, PCM-based thermal storage unit and the indoor cooking unit. Thermic fluid is selected as the heat transfer fluid to exchange the heat between the collector and the cooking unit. PCM A-164 filled in 1 m long, 22 mm diameter tubes will be made as a heat exchanger to store the energy during sunshine hours and to retrieve the energy during off-sunshine hours. The unique characteristic of the cooking unit is the flat surface hot plate, which is similar to the hot plate employed in the electric cooking. Oil will be circulated below the finned hot plate to keep the surface temperature around 140–150 °C. This system can be used at the any time throughout the day for cooking. Though the initial investment needed for the present system is more due to PCM cost, in the long run it becomes cost effective if the PCM at this temperature range is made available at a lower price.

7. Conclusion

A review on the research and development of various types of solar cookers has been carried out. From the review the following conclusions are made.

1. Box type direct solar cookers are well suited to the farmers for their noon meal cooking. It is successfully commercialized in many parts of India.
2. Solar steam cooking using parabolic concentrators are also successfully being utilized for community level large scale noon meal cooking. However, this system has no thermal storage units for cooking during off-sunshine hours.
3. There is some demonstration level modular solar kitchen for residential application. However, a suitable indoor cooking unit for all time cooking similar to the conventional mode is yet to be developed. In the present investigation, the possibility of designing a modular indoor kitchen for commercial and residential application is reported. This may give solution to all prevailing solar cooking problems.

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